Benefits of using Pairwise Trajectory Management in the Central East Pacific

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Pairwise Trajectory Management (PTM) is a concept that utilizes airborne and ground-based capabilities to enable airborne spacing operations in procedural airspace. This concept makes use of updated ground automation, Automatic Dependent Surveillance-Broadcast (ADS-B) and on board avionics generating real time guidance. An experiment was conducted to examine the potential benefits of implementing PTM in the Central East Pacific oceanic region. An explanation of the experiment and some of the results are included in this paper. The PTM concept allowed for an increase in the average time an aircraft is able to spend at its desired flight level and a reduction in fuel burn.

Nomenclature

ADS-B	=	Automatic Dependent Surveillance-Broadcast
ADS-B IN	=	Ability to receive airborne ADS-B broadcast signals
ADS-B OUT	=	Ability to broadcast airborne ADS-B signal
CEP	=	Central East Pacific
FAA	=	Federal Aviation Administration
HITL	=	Human-in-the-loop
NASA	=	National Aeronautics and Space Administration
NATOTS	=	North Atlantic Organized Track System
NM	=	Nautical miles
PACOTS	=	Pacific Organized Track System
PTM	=	Pairwise Trajectory Management
TMX	=	Traffic Manager
WATRS	=	Western Atlantic Track System

I. Introduction

Pairwise Trajectory Management (PTM) is a concept that utilizes airborne and ground-based capabilities to enable airborne spacing operations in oceanic regions [1,2]. The goal of PTM is to use enhanced surveillance, along with airborne tools, to manage the spacing between aircraft. Due to the enhanced airborne surveillance of Automatic Dependent Surveillance-Broadcast (ADS-B) information and reduced communication, the PTM minimum spacing distance will be less than distances or times currently required by air traffic control. Reduced minimum distance will increase the capacity of aircraft operations at a given altitude or volume of airspace, thereby increasing aircraft time on desired, most optimal, trajectories, and therefore, overall flight efficiency.

PTM is designed to allow a flight crew to resolve a specific traffic conflict (or conflicts), identified by air traffic control, while maintaining or enabling the flight crew's desired altitude. The air traffic controller issues a PTM clearance to a flight crew authorized to conduct PTM operations to resolve a conflict for the pair (or pairs) of aircraft (i.e., the PTM aircraft and one or more designated target aircraft). This clearance requires the flight crew of the PTM aircraft to use their ADS-B-enabled onboard equipment and PTM avionics to manage their spacing relative to

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the designated target aircraft to ensure spacing distances that are no closer than the PTM minimum distance. The flight crew will accomplish this Mach-based task by complying with real time guidance generated by the onboard avionics. When the air traffic controller determines that PTM is no longer required, the controller may issue a clearance to cancel the PTM operation.

II. Experiment Design

A fast-time experiment to support the development and evaluation of the PTM concept of operations was conducted at the National Aeronautics and Space Administration (NASA) Langley Research Center. The focus of this experiment was to evaluate the benefits of PTM in the Central East Pacific (CEP) oceanic airspace region. A simulation tool called Traffic Manager (TMX) was used to conduct this experiment. [3] This experiment considered the parameters of ADS-B IN equipage, PTM equipment, PTM separation standard and airspace separation standard. ADS-B IN equipage was varied as a percentage of the aircraft in the airspace, specifically 10%, 20%, 45%, 70%, and 80%. Which aircraft would be equipped with ADS-B IN was assigned randomly. Since the distribution of equipped versus unequipped aircraft could have an impact on the resulting benefit to the system, five iterations were done on the equipage distribution. Each iteration used the same initial conditions for all aircraft but changed which 10%, or higher, percentage of the aircraft were equipped with ADS-B IN. In each specific test case, all ADS-B IN aircraft were either equipped with PTM or none of them were equipped with PTM (this served as the second parameter). It was assumed that all aircraft in the airspace would be equipped with ADS-B OUT, given the Federal Aviation Administration (FAA) 2020 mandate for ADS-B OUT equipment. The PTM separation standard was varied from 5 to 10 nautical miles (NM) for aircraft that were equipped with PTM. The airspace separation standard applied to non-PTM equipped aircraft was 15, 30, or 50 NM. To model the density and distribution of aircraft within the CEP, recorded traffic data were received from the FAA and converted into scenario files that were used in the simulation. This allowed for the experiment to use traffic patterns that are comparable to realistic oceanic operations. A nominal unconstrained airspace was also examined, in which every aircraft was able to fly the exact altitudes that were desired at all times. This was done to provide an upper bound to the maximum benefits possible in the CEP airspace region.

III. Results

The data from this experiment were analyzed to observe the benefits experienced by unequipped aircraft and by PTM equipped aircraft. Several measures were compared between the current day airspace, PTM test case airspace, and the unconstrained airspace to quantify the benefit of PTM. Aircraft equipped with PTM resolved more conflicts which resulted in increased time at optimum flight level and to improvements in fuel efficiency.

A. Fuel Efficiency

Of primary interest during this study was the difference in fuel efficiency, expressed in nautical miles per thousand pounds of fuel as well as percent difference. It is a measure of change in fuel performance between corresponding aircraft in different airspaces. Figure 1 shows the distributions of the percent difference in fuel efficiency above current day for PTM equipped aircraft, unequipped aircraft in the PTM airspace, and the unconstrained airspace. The small values of the y-axis are due to the small range used for the binning of the fuel efficiency values. Unequipped aircraft average no difference over current day while unconstrained and PTM aircraft see improvements. PTM equipped aircraft average an increase of 0.57 NM/1,000lbs over a current day airspace using 50NM non-PTM separation, a 0.93% increase.

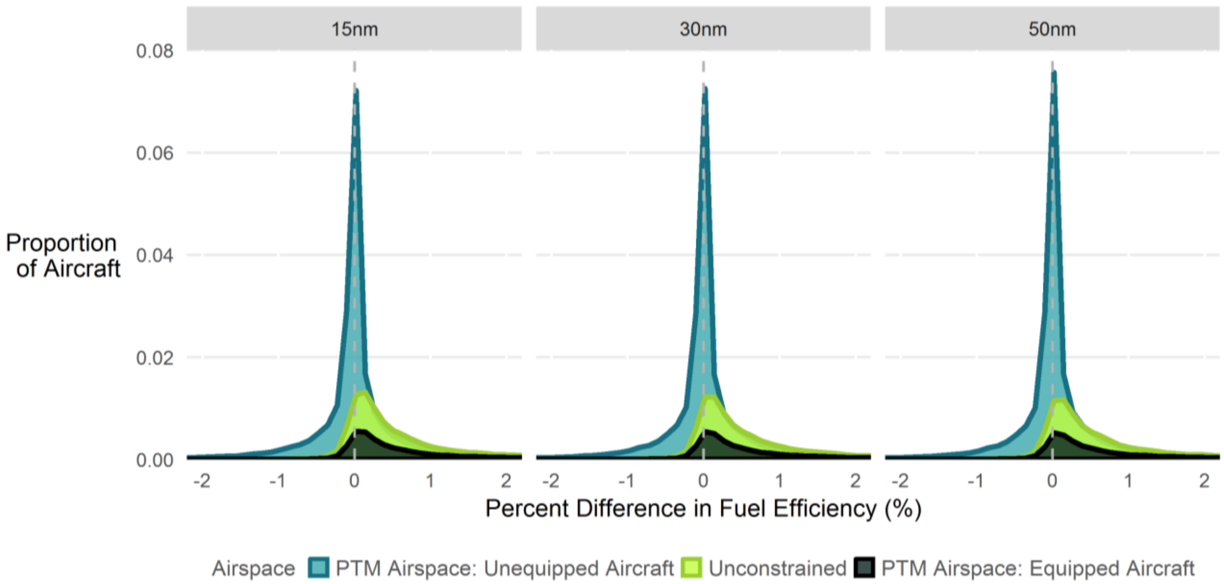

Figure 1. Percent difference in fuel efficiency over current day. *Each panel represents a level of non-PTM separation for the current day airspaces. Unequipped aircraft in the PTM airspace average no difference in fuel burn over current day while unconstrained and PTM equipped aircraft generally see more efficiency than current day across all non-PTM separations.*

Table 1. Mean percent difference in fuel efficiency over current day by airspace.

	Current Day, non-PTM separation						
	15nm		**30nm**		**50nm**		*flights per current day separation*
Airspace	Mean (%)	Std Dev	Mean (%)	Std Dev	Mean (%)	Std Dev	
PTM Airspace: Unequipped Aircraft	0.02	0.76	0.04	0.78	0.06	0.80	*369,074*
PTM Airspace: Equipped Aircraft	0.84	1.52	0.88	1.61	0.93	1.68	*302,276*
Unconstrained	0.88	1.52	0.92	1.59	0.97	1.66	*671,350*

The values listed in Table 1 give average percent differences in fuel efficiency. PTM equipped aircraft see improvements that nearly reach the values gained by unconstrained aircraft. Unequipped aircraft in the PTM airspace see very small gains in fuel efficiency. This was a result of climbs enabled by serving as a designated aircraft in a PTM operation conducted by a PTM equipped aircraft or by the change in altitude of PTM equipped aircraft that created an opening for the unequipped aircraft to climb into. It is desired to not introduce a burden on those aircraft operators that choose not to equip with the new technology by introducing PTM operations.

These values are averages of the data, including all levels of PTM separation and airspace equipage. This aggregate data set does show a non-normal distribution. Separating these levels and testing for differences was done using analysis of variance (ANOVA). PTM equipped and unequipped aircraft were separated because they have quite different fuel efficiency distributions. PTM equipment (PTM equipped or unequipped), PTM separation (5 or 10 NM), and airspace equipage (10, 20, 45, 70, or 80% of the airspace equipped with PTM) were variables included in the ANOVA at each level of current separation (15, 30 and 50 NM). The relationships between the variables of interest changed across the levels of current day separation. Within each current day separation, PTM equipped aircraft had larger fuel efficiency gains than unequipped, though the separation that the PTM aircraft used (either 5 or 10 NM) did not have statistical significance in the 15 and 30 NM current day separation cases (p-value > 0.05).

The PTM separation was important in the 50 NM case in the form of a three-way interaction with the other experiment variables. Airspace equipage levels also affected fuel efficiency gain (p-values < 0.001), with some level of interaction with other variables at 30 and 50 NM current day separation.

Statistical differences in levels of PTM equipment were deemed operationally or practically significant by the researchers while the differences in levels of PTM separation and airspace equipage, if found to be statistically significant, were not deemed practical. For example the range of values from 10% to 80% airspace equipage in the 50 NM case for PTM equipped aircraft only increase from 0.90% to 0.94% improvement in fuel efficiency. That range is not as substantial as the range in PTM equipment levels from unequipped to PTM equipped (0.06% up to 0.93% in the 50 NM case).

These variables chosen in the experiment turned out not to have a large effect on fuel burn. Other variables that were built into the simulation, like type of aircraft and the flight level where the aircraft began the simulation, had larger effects on fuel burn. Using percent difference of fuel efficiency reduces some variability due to aircraft type, as some types generally carry and burn more fuel than others. Some variability remains between aircraft types, though most types see gains of around 1%, shown in Figure 2.

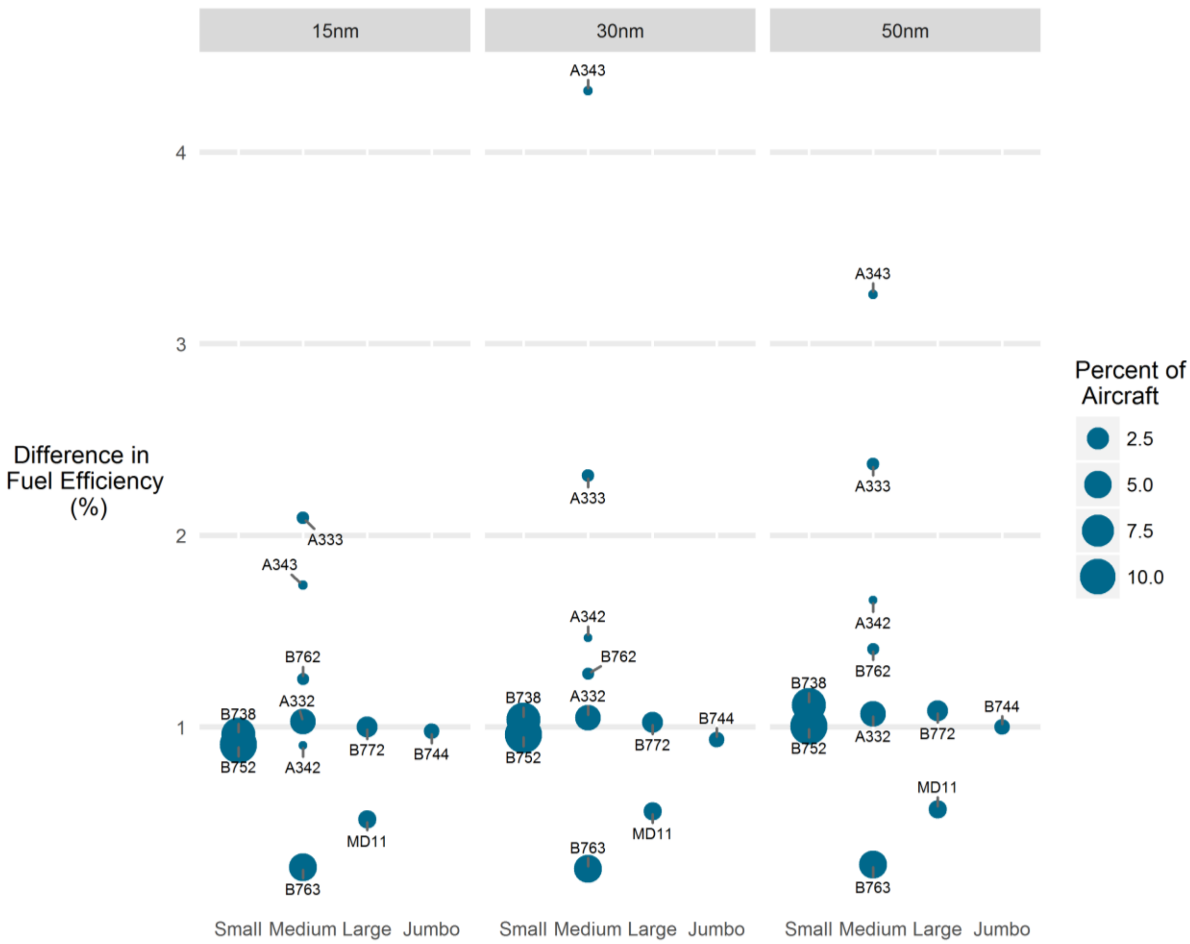

Figure 2. Percent difference in fuel efficiency for PTM equipped aircraft, sorted by type and size of aircraft. *Size of points corresponds to percent of aircraft in that category. Most aircraft that are equipped with PTM see around 1% increase in efficiency.*

Another variable that affects fuel burn is delta flight level. Each aircraft began the scenario at some altitude, which may or may not be close to the optimal altitude for that aircraft. The aircraft began their flight at an altitude based on real world traffic data, however the mass of the aircraft was unavailable in the data. This could result in a difference between the optimal altitude for each the aircraft in the real world versus the calculated optimal altitude in the simulation. The difference between initial altitude and calculated optimal altitude, delta flight level, was recorded for each flight. Aircraft that started further from their optimal altitude saw larger gains in fuel efficiency

(over 10% in some cases that were 10,000 feet below their optimum at the start), while those closer to their optimal averaged much smaller gains. Aircraft below their optimum altitude have more to gain by climbing to a more optimal altitude. The aircraft compared between PTM and current day cases share the same delta flight level value at the start of the scenario, which should somewhat control for this effect, but the trend still exists.

The relationships between fuel efficiency and the independent variables specifically varied in the experiment (as well as other characteristics of the data, such as aircraft type and delta flight level) are summarized in the partition tree below. A partition tree splits data according to relationships between the dependent and independent variables, and then repeats the process, creating a tree of splits in the data. The resulting tree, Figure 3, shows that most of the variability in fuel efficiency can be attributed to delta flight level or PTM equipment. The experimental independent variables were not found to add enough value, which is consistent with the ANOVA analysis above.

Listed in each leaf is the mean percent difference in fuel efficiency above current day, with a dot showing the percent of aircraft that fall under that leaf (0% to 100% left to right). The left most leaf shows that around 50% of the simulated flights were unequipped and started no less than 2,500 feet below their optimum flight level, and they gained only 0.02% in fuel efficiency. Less than 1% of aircraft fell into the rightmost leaf which saw over 8% improvement.

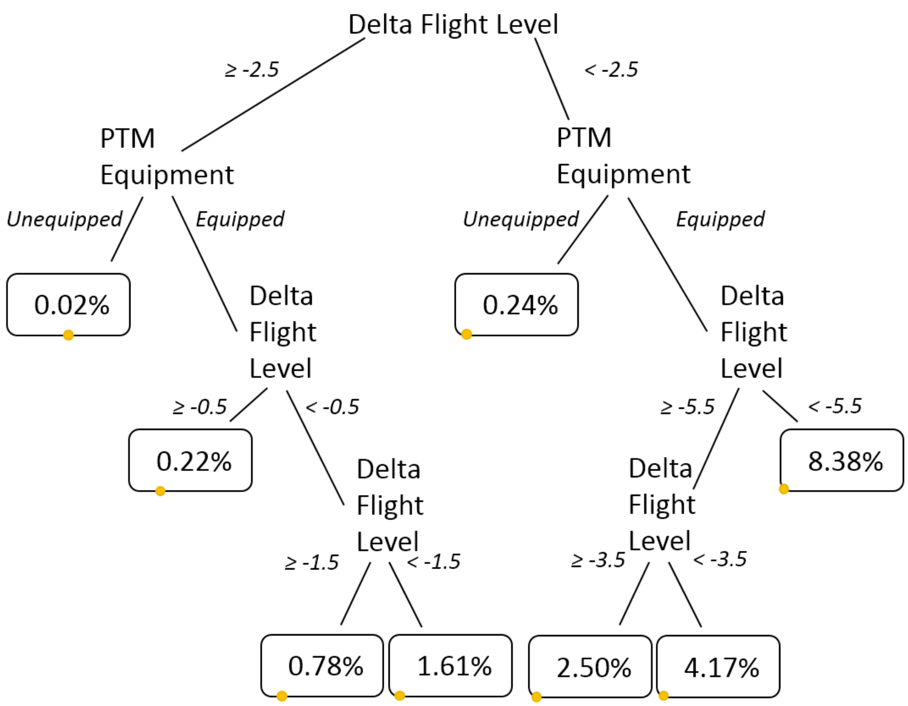

Figure 3. Partition tree of percent difference in fuel efficiency over current day. *The first split in the data, which accounts for the most variability in the percent difference, is how far an aircraft was loaded from its optimum at the start of the scenario.*

B. Time on Optimum Altitude

Differences in aircraft time spent on optimum altitude between the three airspaces (PTM, current day and unconstrained) are another measure of interest. For each flight, the amount of time spent on its optimum flight level was recorded and converted to a percentage of total flight time.

Figure 4 shows the distributions of the three airspaces for each level of non-PTM separation standard. The PTM airspace is broken down into PTM equipped and unequipped aircraft. PTM aircraft have a distribution close to the unconstrained distribution, and unequipped aircraft have values closer to the current day airspace. The average PTM equipped flight spends around 91% of its flight on optimum, unconstrained aircraft average 96%, while current day aircraft average around 37% with unequipped aircraft in the PTM airspace seeing 38% on average. The distributions look similar across non-PTM separation standards; however, at 50 NM there are more current day flights getting nearly 0% on optimum.

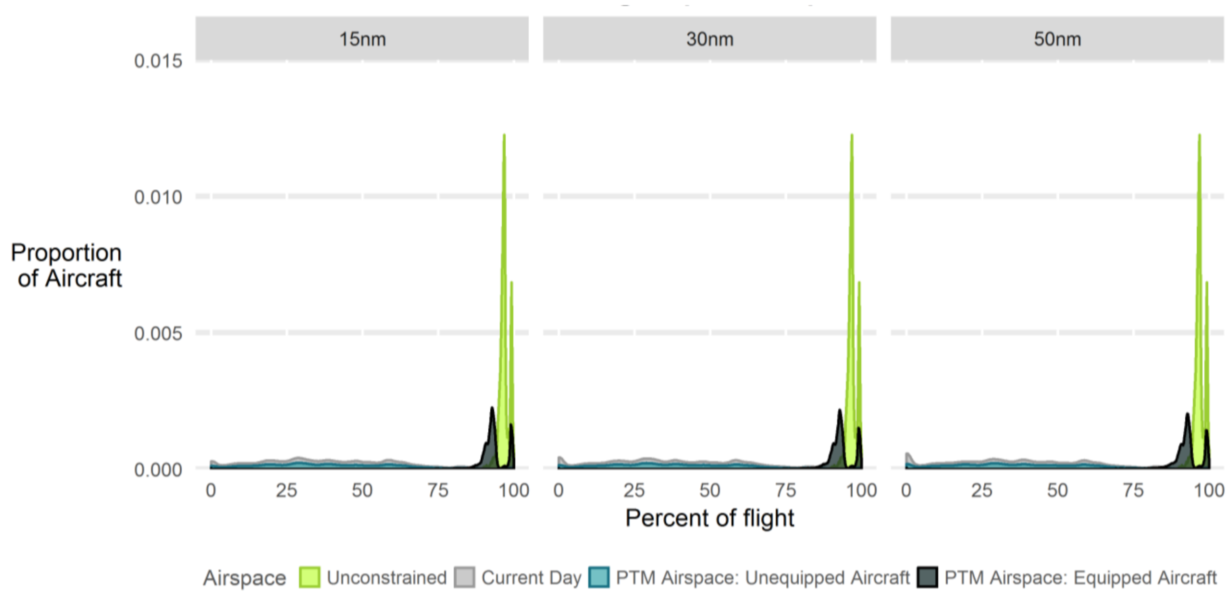

Figure 4. Distribution of percent of flight time on optimum altitude by airspace. *PTM Equipped aircraft get close to the unconstrained values. Unequipped aircraft in the PTM airspace and current day airspace have similarly distributed time on optimum values.*

C. PTM Operations

The technology on the PTM equipped flights enables smarter, more frequent altitude requests, as well as reduced separation to resolve conflicts with another aircraft (this will be called a PTM operation). Not every PTM equipped flight saw a conflict along their route so many did not complete a PTM operation, though they still got the benefit of frequent requests. The percent of PTM equipped flights that did one or more PTM operations increased from an average of 6% to 10% to 15% across the levels of current day separation (15, 30, and 50 NM). With larger current day separations to maintain and the same number of aircraft in the airspace, there are more conflicts to resolve in the 50 NM case.

The number of unique PTM operations per flight is also of interest to gauge the utility of PTM. Each PTM equipped aircraft that used PTM did so 1.5 times on average per flight. Some flights completed up to 7 PTM operations but most did one or two. This trend is consistent across PTM separation, current day separation, and airspace equipage.

A single ownship can do a PTM operation with one or more designated targets. Aircraft that used PTM usually spent around 50 minutes total per flight with one target. Time spent with two or more designated targets averaged only approximately one minute. Generally, aircraft that completed a PTM operation during their flight did so one time with one target aircraft.

The fuel efficiency gained by PTM equipped flights that did and did not complete a PTM operation is shown in Table 2. Aircraft that used PTM at least once during their flight averaged nearly 1.5% increase in fuel efficiency, while those that were equipped with PTM but did not use it still saw an increase of 0.63%, averaged across levels of current day separation. Those that did not do a PTM operation saw this benefit from merely making better altitude requests. Those that completed a PTM operation saw a fuel efficiency increase that is larger than the value for the average unconstrained aircraft of 0.97% given in Table 1. This value is an average and has a standard deviation of 1.66, meaning some subgroups of aircraft see more or less fuel efficiency improvement over current day. When matched with their PTM counterparts that completed at least one operation, the improvement of unconstrained aircraft reached 1.54%, meaning the PTM equipped aircraft perform close to, but not better than, those that were unconstrained.

Table 2. Mean percent difference in fuel efficiency over current day of PTM equipped aircraft broken down by number of operations.

	Current Day, non-PTM separation						
	15nm		**30nm**		**50nm**		*flights per current day separation*
PTM Use	Mean (%)	Std Dev	Mean (%)	Std Dev	Mean (%)	Std Dev	
No PTM operations	0.61	1.37	0.63	1.40	0.65	1.44	*283,349*
At least one PTM operation	1.41	2.30	1.47	2.37	1.52	2.37	*18,927*

IV. Conclusions

PTM does provide benefit by resolving conflicts in the CEP, leading to fuel burn reduction and increased time at optimum altitude. Aircraft that completed at least one PTM operation during their flight saw increased fuel efficiency of 1.5% over the 50 NM current day case. PTM equipped aircraft that did not do any PTM operations saw small but operationally relevant gains and unequipped aircraft saw marginal gains in fuel efficiency. Introducing PTM to the airspace does not negatively affect aircraft that are not equipped with the technology.

The amount of time flights spent at optimum altitude greatly increased for PTM equipped aircraft compared to flights in the current day airspace. The average for flights in the current CEP airspaces (with 15, 30, and 50 NM separations) is between 36 and 38% and the average for the unconstrained airspace is 97%. PTM equipped aircraft see greater benefit over unequipped aircraft, averaging up to 91% of the time at optimum altitudes, compared to 38% for unequipped aircraft. By equipping with PTM, aircraft see benefit in terms of altitude requests, fuel savings, and time flying at their optimum altitude.

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